

Sustainable Structures Unveiled: Navigating the Environmental Landscape of 3D Printing in Construction [†]

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Abstract: This study addresses the imperative for sustainability in the construction industry, focusing on the environmental impact of a specific 3D printing method. Leveraging insights from an engineering-orientated 3D printing project, diverse scenarios are explored, and a cradle-to-gate life cycle assessment (LCA) is conducted using SimaPro 9.5.0 software. The study reveals the efficacy of a mix design with fly ash and furnace slag as a binder, demonstrating lower environmental impacts in various categories. However, the inclusion of silicate in geo-polymer concrete raises ecological concerns due to the high energy requirements for production. Additionally, substituting sand with sawdust results in a substantial reduction in CO₂ emissions, highlighting the environmental benefits of incorporating by-product materials into building practices.

Keywords: life cycle assessment; additive manufacturing; sustainability; green concrete; environmental footprint; geo-polymer (GP) concrete

1. Introduction

Due to a recent increase in energy use, resulting in higher CO₂ emissions, researchers are now paying more attention to environmental issues. The construction industry, in particular, is a significant focus, with ongoing efforts to reduce energy use and minimize emissions. This sector is accountable for about 35% of worldwide energy consumption and carbon dioxide emissions [1]. Despite the challenges of waste production and quality control linked to traditional building methods like timber, on-site concrete casting, and brickwork, these methods continue to be widely used in construction. This underscores the urgent requirement for more efficient, innovative, and environmentally friendly approaches to construction. These advancements seek to meet the needs of today's built environment and tackle the socio-economic challenges facing the construction industry [2]. Recently, 3D printing, also known as additive manufacturing (AM), has emerged as a pivotal element of the technological revolution, Industry 4.0, and is being considered as a potential solution to the aforementioned challenges [3]. With its design flexibility, extensive material selection, and efficient manufacturing processes, 3D printing is proving to be a beneficial tool across various industries [4]. Specifically, 3D concrete printing (3DCP) stands out as a comprehensive response to the growing demand for ecological and sustainable methods for cement-based construction. By significantly reducing both the physical and functional energy required for constructions, 3DCP is contributing to a substantial decrease in carbon footprints [5]. WASP (World's Advanced Saving Project) and Mario Cucinella Architects demonstrated the use of 3D printing in building design through the Tecla project [6]. Tecla's structures in Massa Lombarda, Italy, showcase effective insulation and ventilation using the Crane WASP 3D printer. Introduced in 2021, this system enables the efficient and sustainable construction of 3D-printed houses, crafting large and intricate



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structures. WASP on Site sets a standard for innovative construction methods, incorporating local materials to reduce CO₂ emissions [6]. The project's focus on sustainability, using local materials, is acknowledged. However, key questions need further investigation. Specifically, what environmental impacts might arise from using a validated concrete mix design in the 3D printer's slurry system? Additionally, could emissions be reduced by adjusting mix designs? This study aims to comprehensively address these questions, crucial in thoroughly assessing the project's environmental impact. Drawing on information from the Tecla project, this research hypothesizes about the ecological effects of different mix designs in 3D concrete printing. This study explores four mix designs, compiling data on energy and material input and assessing diverse environmental consequences. The primary goal is to investigate the ecological impacts of employing 3DCP. The WASP Crane system Arrangement is illustrated in Figure 1, showcasing the innovative design used for 3D printing in construction [7].



Figure 1. The WASP Crane system Arrangement © WASP.

2. Life Cycle Assessment

The study utilizes the life cycle assessment (LCA) method, following ISO standards 14040-44, to evaluate environmental impacts. Using SimaPro software and the Ecoinvent v3.1 database, the LCA examines the environmental effects of processes and products throughout their life cycle. The LCA methodology involves defining the goal and scope, establishing system boundaries, identifying the functional unit of analysis, and examining environmental impact categories.

2.1. Goal, Scope, Functional Unit, and System Boundary

The objective of this study is to assess the environmental impact of a 3D-printed house using different designs (scenarios A, B, C, and D) in Attawapiskat, chosen due to the housing crisis faced by this community [8]. The functional unit is a 130-square-meter house printed by the Crane WASP 3D printer. This size is selected considering that the average house size in Canada is about 181 square meters [9], with variations based on province, house type, and factors like personal preferences, lifestyle, and budget considerations affecting family home space requirements. In Attawapiskat, where the average family size is 3.7 people [10], the recommended home space per person is typically between 18.58 and 65.03 square meters [11]. Therefore, for a family of 3.7 people in Attawapiskat, the suggested home space would be around 68.74 to 240.52 square meters. A cradle-to-gate assessment is regarded as the system boundary in this evaluation. Figure 2 depicts the system boundary in this study.

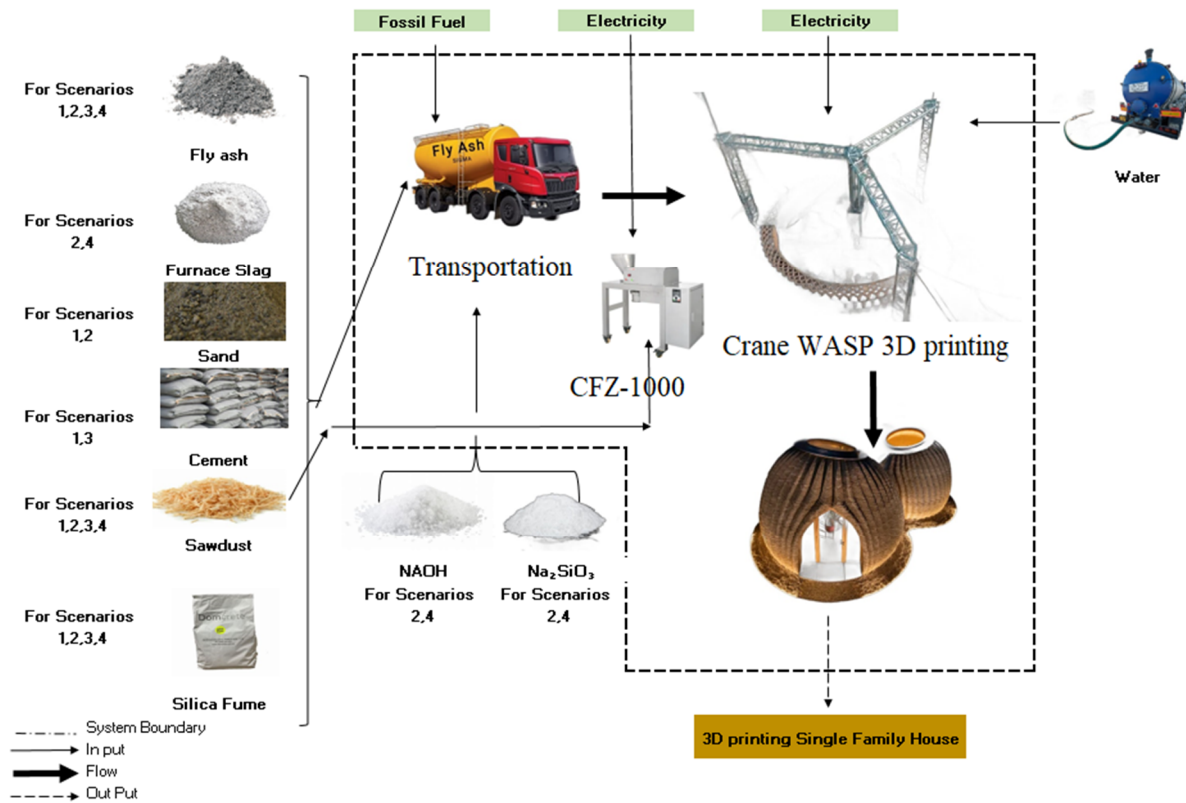


Figure 2. System boundary for the 3DC printing construction methods.

2.2. Life Cycle Inventory

The selection of mix designs in this research is based on their previous usage in 3D printing studies and their incorporation of geo-polymer substances such as fly ash or blast furnace slag. The objective behind opting for geo-polymer lies in adopting a proven mix design that integrates by-products, effectively minimizing the environmental impact. Mix designs for the 3D-printed concrete scenarios were adapted from materials commonly used in the literature [12–15]. An experimental approach involved replacing sand with sawdust in the concrete mixture. In Scenarios A and B, 50% of the sand was replaced with sawdust, while in Scenarios C and D, the sand was entirely replaced with sawdust (100% replacement). An innovative approach to sustainable waste management involves incorporating sawdust into concrete and cement-based composites. Lightweight concretes (LWCs), as studied by Mehdi et al. in 2023, offer cost-effectiveness, improved handling, and enhanced properties. Substituting natural aggregate with sawdust reduces compressive strength by 35%, but boosts sound absorption by 38%, and reduces thermal conductivity by about 4.5 times [16]. Additional essential data for the life cycle assessment model are sourced from available information from the Tecla project [17]. For example, in computing the electricity consumption in the 3D printing machine, we extrapolate the energy usage based on the parameters of the project, subsequently customizing it to fit our structure spanning 130 m². According to data provided by Tecla, their project involved a printing duration of 200 h, with an average electricity consumption of under 6 kW. Adjusting these parameters to align with our specific project and utilizing the same Crane WASP 3D printer, we estimate that the energy required for printing a house covering an area of 130 m² would be approximately 13 kW, with an anticipated printing duration of around 433.3 h. Table 1 provides a comprehensive breakdown of these assessments. Moreover, the direct inclusion of sawdust into concrete ink is not feasible; it necessitates size reduction for printability. Despite sawdust being a by-product, it is crucial to acknowledge that the size reduction process entails electricity consumption, contributing to its own environmental impact.

Table 1. Crane WASP 3D printer features for Tecla and Attawapiskat projects.

Features	Tecla Project	Attawapiskat Project
Size of house	60 m ²	130 m ²
Material usage (18 mm nozzle)	38.151 m ³	82.66 m ³
Printing time	200 h	433.3 h
Electricity consumption	6 KW	13 KW

Table 2 presents the life cycle inventory for the 3D printing scenarios, outlining the energy consumption during construction, the electricity needs for 3D printing, and the materials needed for printing the house and transformation data, which represent the distance from potential material sources to the construction site in Attawapiskat city.

Table 2. Life cycle inventory for 3D printing scenarios.

Items	Unit	Scenario A	Scenario B	Scenario C	Scenario D	Distance t* km
Fly ash	kg	13,638.90	49,805.13	13,638.90	49,805.13	0.955
Slag	kg	-	8788.41	-	8788.41	0.955
Sand	kg	51,290.53	43,946.19	-	-	0.683
Na ₂ SiO ₃	kg	-	14,498.56	-	14,498.56	1.336
NaOH	kg	-	11,869.98	-	11,869.98	1.336
Water	kg	19,177.12	4882.73	19,177.12	4882.73	0.100
Cement	kg	47,860.14	-	47,860.14	-	0.683
Sawdust	kg	51,290.53	43,946.19	102,581.06	87,892.38	0.100
Silica fume	kg	6860.78	4882.73	6860.78	4882.73	0.955
Electricity	MJ	21,293.99	21,148.57	22,309.54	22,018.71	-

2.3. Life Cycle Impact Assessment

In this study, we opted for Recipe Endpoint H for specific reasons, primarily driven by our focus on assessing the ecological impact of the building process at the endpoint level, where Recipe provides pertinent emissions data. The selection of methods, such as Traci and LIME, depends on the investigation's depth, but Recipe is widely favored in this research field. Additionally, Recipe comprehensively covers various environmental categories, encompassing global warming, stratospheric ozone, ionizing radiation, ozone formation, fine particulate matter, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogens, human non-carcinogens, land use, mineral resources, fossil resources, and water consumption.

3. Finding and Interpretation

The provided data emphasize the primary factors influencing the environmental impact in each scenario. Cement plays a substantial role in Scenarios A and C, while transportation and sodium silicate are prominent in Scenarios B and D. These findings align with other studies in the field. For example, studies by Mohammad et al. [18], Abdalla et al. [19], and Sambucci et al. [20] revealed cement contributions of 78%, 97%, and 92% respectively. Various studies underscore the significant environmental impact associated with cement and concrete production. Silicate, especially in sodium silicate production, is frequently highlighted in studies for its notable environmental effects. For instance, Yao and colleagues [21] found in their research that reducing the amount of silicate in the geo-polymer recipe is an effective means of mitigating the ecological consequences of 3D concrete.

Comparing Scenarios

Figure 3 illustrates a comparison of the life cycle environmental impacts among different 3D concrete printing scenarios, with a focus on various materials outlined in the four

previously mentioned scenarios. Within these scenarios, Scenario A exhibits the highest impact on the environment in terms of climate change, photochemical oxidants, particulate matter formation, terrestrial acidification, freshwater eutrophication, and natural land transformation. Conversely, Scenario B has the most significant impact on ozone depletion, human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, metal depletion, and fossil depletion. Scenario C shows the lowest impact on agricultural land occupation and ozone depletion, while Scenario D has the least impact on natural land transformation, terrestrial acidification, and climate change.

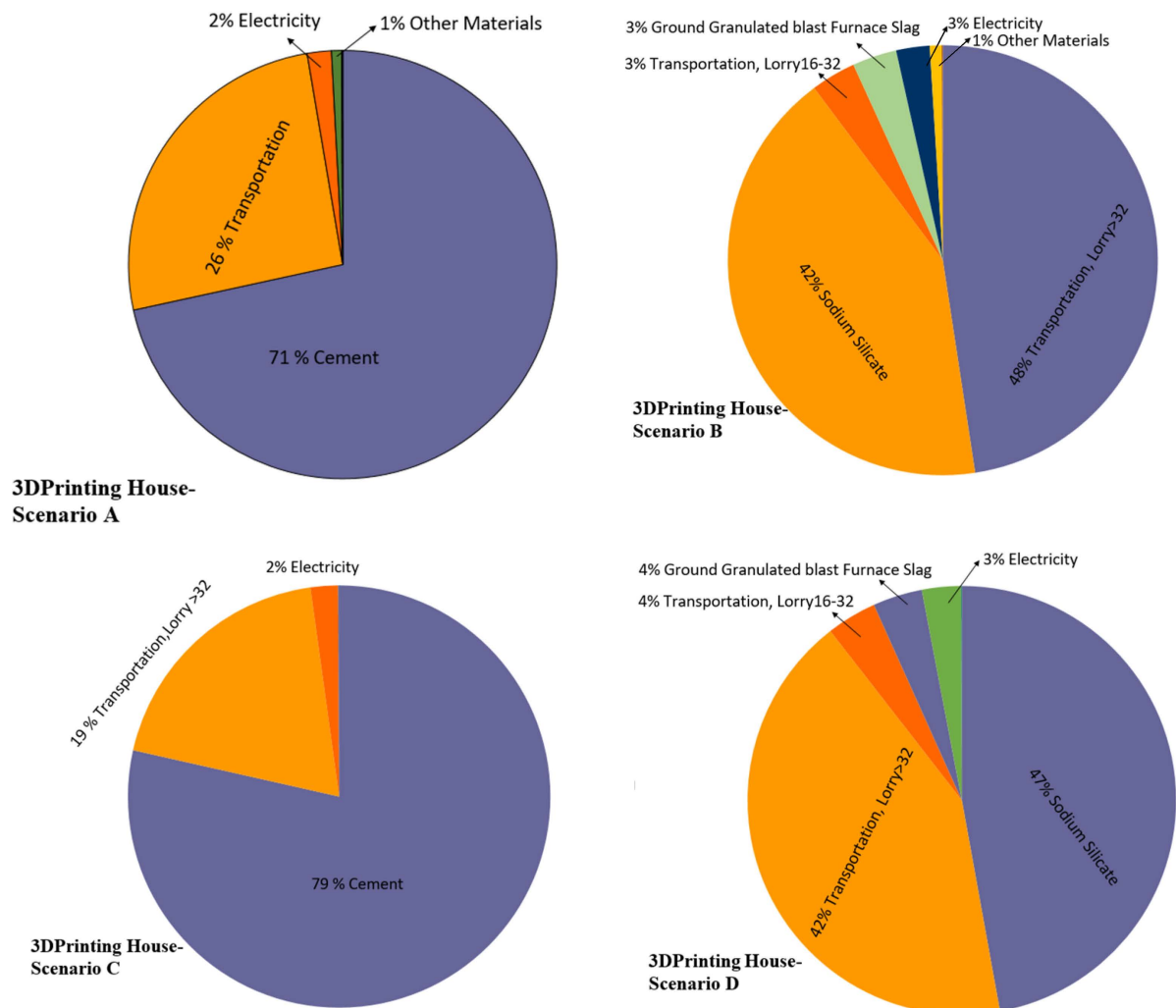


Figure 3. The primary contributing factors to ecological impact in each scenario.

Scenarios B and D have a significant impact on the environment across a wide range of categories due to their involvement in the sodium silicate manufacturing process. The results also indicate that integrating sawdust into the mix design for 3D printing applications leads to a reduction in emissions across all environmental categories. For instance, replacing sand entirely with sawdust in Scenarios 1 to 3 resulted in a decrease in CO₂ emissions from 47.57 tons to 44.81 tons. Similarly, in Scenarios 2 to 4, this quantity decreased from 24.31 tons to 21.95 tons. Figure 4 illustrates comparative analysis of environmental impact across all scenarios.

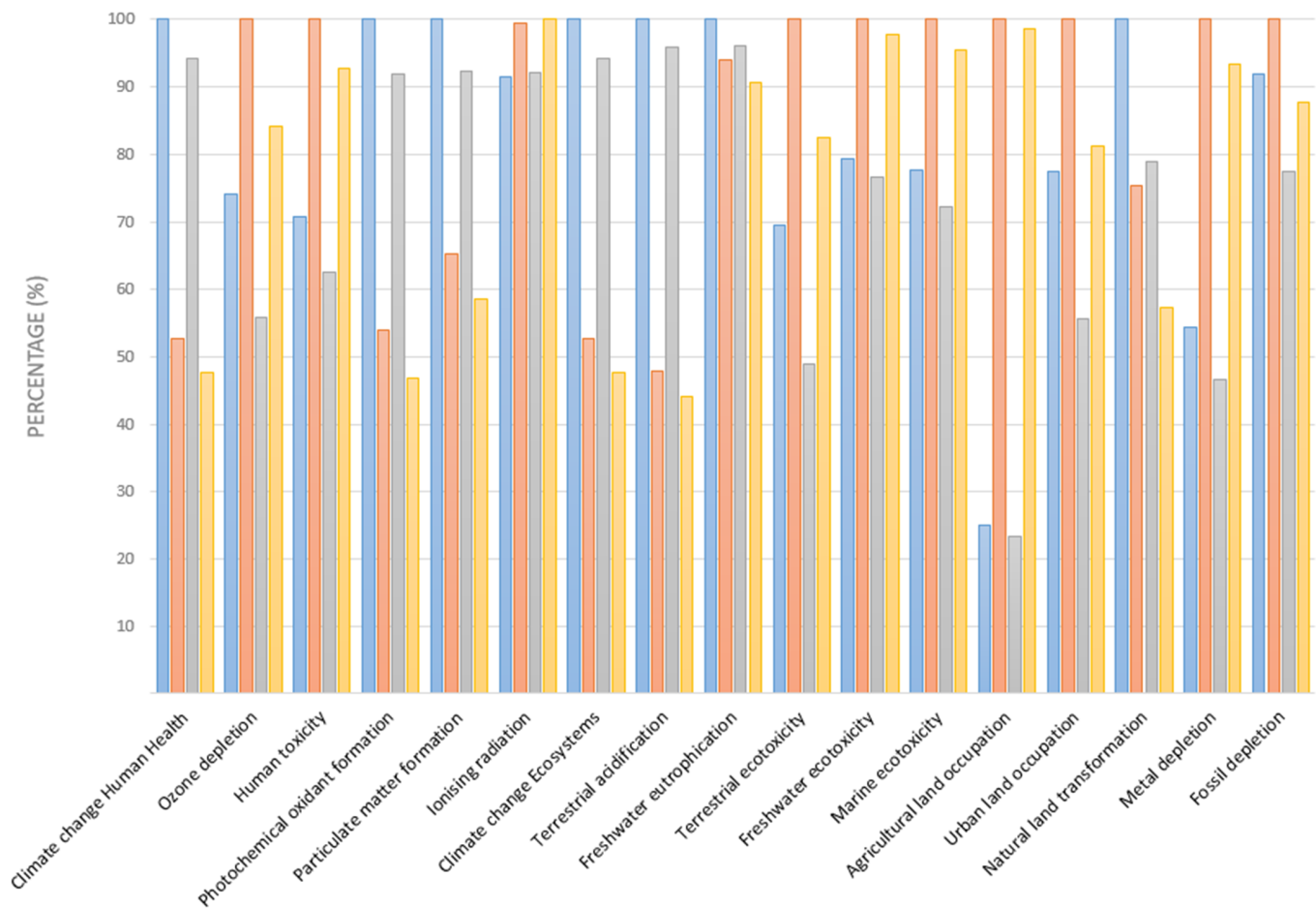


Figure 4. Comparative analysis of environmental impact across four scenarios. (Scenario A: blue, Scenario B: red, Scenario C: gray, and Scenario D: orange.)

4. Conclusions

This study sheds light on the critical role of sustainability in the construction sector, particularly within the realm of 3D printing technologies. By examining the environmental impacts of different mix designs and materials, this research highlights the potential for reducing carbon footprints through the strategic use of binders like fly ash and furnace slag. Through the application of life cycle assessments, this study emphasizes the importance of evaluating the overall environmental footprint of construction processes. By exploring various scenarios and mix designs (Scenarios A, B, C, and D), this research provides valuable insights into enhancing eco-friendly practices and lowering environmental burdens in construction. Embracing sustainable approaches, including the adoption of innovative materials and technologies such as 3D concrete printing, offers a promising pathway towards a more environmentally conscious and sustainable construction industry.

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